

Magellanic Cloud planetary nebulae as probes of stellar evolution and populations

Letizia Stanghellini

Space Telescope Science Institute, and European Space Agency

Abstract. Magellanic Cloud Planetary Nebulae (PNs) offer insight of both the population and evolution of low- and intermediate-mass stars, in environments that are free of the distance bias and the differential reddening that hinder the observations of the Galactic sample. The study of LMC and SMC PNs also offers the direct comparison of stellar populations with different metallicity. We present a selection of the results from our recent *HST* surveys, including (1) the morphological analysis of Magellanic PNs, and the statistics of the morphological samples in the LMC and the SMC; (2) the surface brightness versus radius relationship; and (3) the analysis and modeling of the [O III]/H β PN luminosity functions in the LMC and the SMC.

1. Introduction

Planetary Nebulae (PNs) are important probes of stellar evolution, stellar populations, and cosmic recycling. PNs have been observed in the Local Group as well as in external galaxies, probing stellar evolution and populations in relation to their environment.

The details of the observations of Galactic PNs and their central stars (CSs) typically surpass the details of stellar and hydrodynamic models. Galactic PN studies are a necessary background toward the understanding the PN populations in general. Yet, the distance scale of Galactic PNs is uncertain to such a degree that the meaning of the comparison between observations and theory is hindered. By the same token, statistical studies of PN populations in the Galaxy suffer for the observational bias against the detection of Galactic disk PNs, and for the patchy interstellar extinction.

PNs in the Magellanic Clouds (LMC, SMC), hundreds of low-extinction planetaries at uniformly known distances, are a real bounty for the stellar evolution scientist. The composition gradient between the LMC, the SMC, and the Galaxy, afford the study of the effects of environment metallicity on PN evolution. The relative vicinity of the Clouds, and the spatial resolution that can be achieved with the *Hubble Space Telescope (HST)*, allow the detection of PN morphology. Studying the PNs in the Magellanic Clouds is a necessary step toward the understanding of the onset of morphological type and its relation to metallicity and stellar evolution.

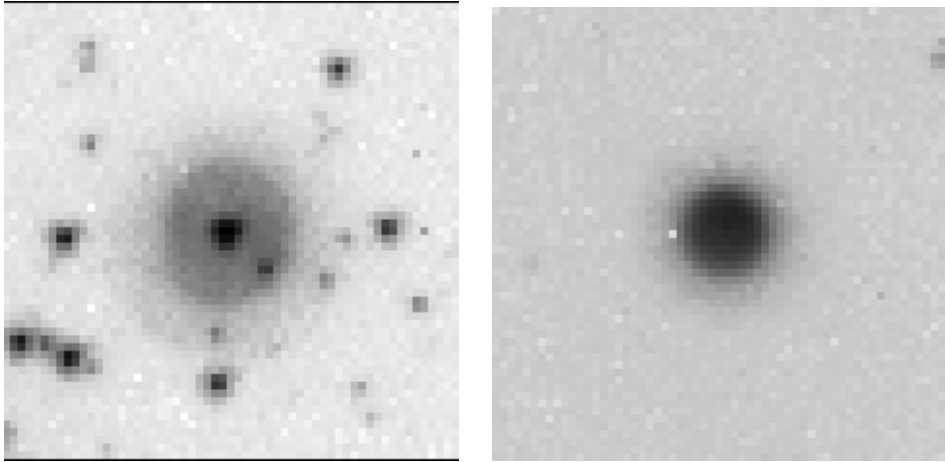


Figure 1. Round PNs: LMC J 33 and SMC SP 34.

2. Our Magellanic PN program

During the *HST* Cycle 8 we started a series of surveys aimed at obtain the size, morphology, and CS properties of all Magellanic PNs known to date. The *HST* was an obligatory choice, since the Magellanic PNs are typically half an arcsecond across, thus they are generally not resolved with ground-based telescopes.

The medium-dispersion, slitless capability of STIS offers us a valuable opportunity to study the evolution and morphology of the Magellanic Cloud PNs and their CSs at once. We have applied this capability in several SNAPSHOT surveys, obtaining images in the light of up to 7 of the most prominent low- and moderate-ionization optical, nebular emission lines (*HST* programs 8271, 8663, and 9077). We also obtained direct continuum images to identify the correct CS (in spite of the crowded fields), and to measure the optical continuum emission.

In addition to the optical slitless spectra and broad band continuum images of the LMC and SMC PNs, we have acquired STIS UV spectra of 24 LMC PNs. In the cases where the CSs were hard to find in our STIS broad band images, we have also acquired WFPC2 Strömgren images (Program 8702). We have used through our investigations the limited data available in the literature (see Stanghellini et al. 1999). The data acquired by us with *HST* can be easily retrieved from the dedicated MAST page <http://archive.stsci.edu/hst/mcpn>. In addition to *HST*, we have made extensive use of the spectra acquired from the ground by us (papers in preparation), and available in the literature.

2.1. PN morphology

The morphology of Galactic PNs has been studied rather thoroughly in the past decade, and it has been found that the morphological types correlate with the PN progenitor's evolutionary history, and the stellar mass. There is strong evidence that asymmetric (e. g., bipolar) PNs are the progeny of the massive AGB progenitors (3-8 M_{\odot}). Bipolar PNs are nitrogen enriched and carbon poor (Stanghellini et al. 2002b). The analysis of the morphological types and their

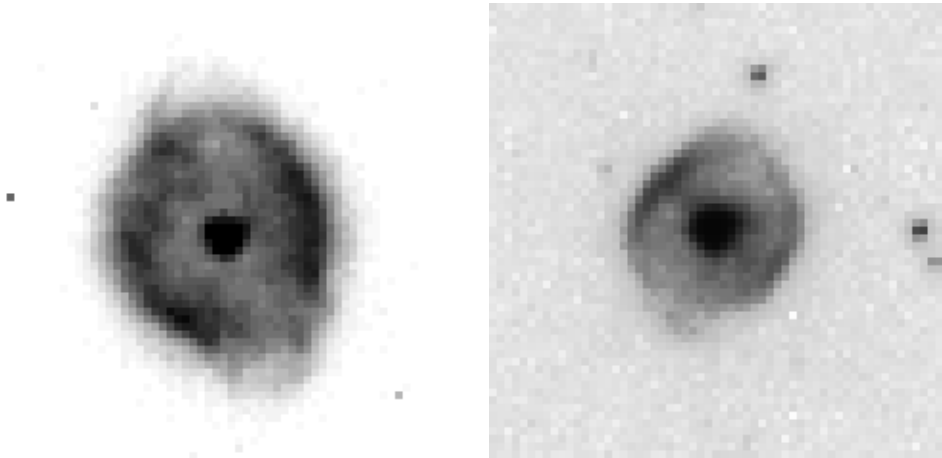


Figure 2. Elliptical PNs: LMC SMP 101 and SMC MG 8.

distribution in a PN population is then very useful to infer the age and history of a given stellar sample.

Galactic PNs have been classified as round, elliptical, bipolar (and quadrupolar), bipolar core (those bipolar PNs whose lobes are too faint to be detected, but whose equatorial ring is very evident), and point-symmetric. The majority of Galactic PNs are elliptical, but the actual number of bipolars could be underestimated, given that they typically lie in the Galactic plane (i.e., they may suffer high reddening).

In Figures 1 through 3 we show samplers of the most common morphological types of Magellanic PNs, round, elliptical, and bipolar. These PNs are more than 50 times farther away than the typical galactic PNs, yet the major morphological features are easily recognized, as are the location of their CSs, when visible.

PNs in the Clouds, when spatially resolved, show the same admixture of morphological types than the Galactic PNs. While we do not attempt a statistical comparison of the MC and Galactic PN morphological types, given the selection effects that hamper Galactic PNs, we can meaningfully compare the LMC and SMC samples. Both samples suffer from low field extinction, and they have been preselected in more or less the same way.

The results of the morphological distribution in the Clouds is summarized in Table 1. Together with the percentage in each morphological class, we give the total of symmetric (round and elliptical) and asymmetric (bipolar and bipolar core) PNs. One striking difference between the two distributions is that the fraction of bipolar PNs in the LMC is almost six times that of the SMC. Bipolar PNs are easily recognized, thus this is a sound result. If we add to the asymmetric PN count the bipolar core PNs, we obtain that half of the LMC PNs are asymmetric, while only a third of the SMC PNs are asymmetric. Observational biases play in the same way for the two samples.

What insight can we get from the morphological results? First of all, it is clear that the set of processes that are involved in the formation of the different PN shapes are at work *in all galaxies where morphology has been studied*. Second, the SMC environment may disfavor the onset of bipolarity in PNs. Otherwise,

Table 1. Morphological distribution

Morphological type	% LMC	% SMC
Round (R)	29	35
Elliptical (E)	17	29
R+E (symm.)	46	64
Bipolar (B)	34	6
Bipolar core (BC)	17	24
B+BC (asymm.)	51	30
Point-symmetric (P)	3	6

the different morphological statistics may indicate different populations of stellar progenitors in the two Clouds. While it seems reasonable to conclude that a low metallicity environment is unfavorable to bipolar evolution, the exact causes have not been studied yet. A detailed study of metallicity and mass loss may clarify this point. On the other hand, the different morphological statistics may simply be related to a lower average stellar mass of the PN progenitors in the SMC. If this was the case, we should observe also lower CS masses in the SMC PNs than in the LMC PNs. Our preliminary measurements seem to indicate that this is also the case (Villaver, Stanghellini, & Shaw, in preparation).

2.2. Surface brightness evolution

The surface brightness of LMC and SMC PNs correlates with the photometric radius (Stanghellini et al. 2002a, 2003a). The surface brightness- photometric radius relation is tight in all spectral lines, with the exception of the [N II] emission line, where a larger spread is present, particularly for bipolar PNs. A possible factor is the larger range of nitrogen abundances in bipolar and BC PNs. The surface brightness- photometric radius relations hold only in the cases in which the nebular density N_e is smaller than the critical density, N_{crit} (the density at which the collisional de-excitation rate balances the radiative transition rate).

A good eye-fit to the surface brightness- photometric radius relation is $SB \propto R_{\text{phot}}^{-3}$. This relation can be reproduced via hydrodynamic modeling of evolving PNs and their CSs (Villaver & Stanghellini, in preparation). The surface brightness- photometric radius relation in the light of $H\alpha$ (or $H\beta$) is tight enough that it can be used to set the distance scale for Galactic PNs with intrinsic uncertainties of the order of 30% or less (Stanghellini et al. in preparation), while the current calibration of the Galactic PN distance scales carry errors of the order of 50% or more.

In the surface brightness- photometric radius relation we note that the symmetric (round and elliptical) PNs tend to cluster at high surface brightness and low radii, while the asymmetric PNs occupy the lower right parts of the diagrams. This separation can be interpreted with a slower evolutionary rate for the symmetric PNs, which agrees with the idea that symmetric PNs derive

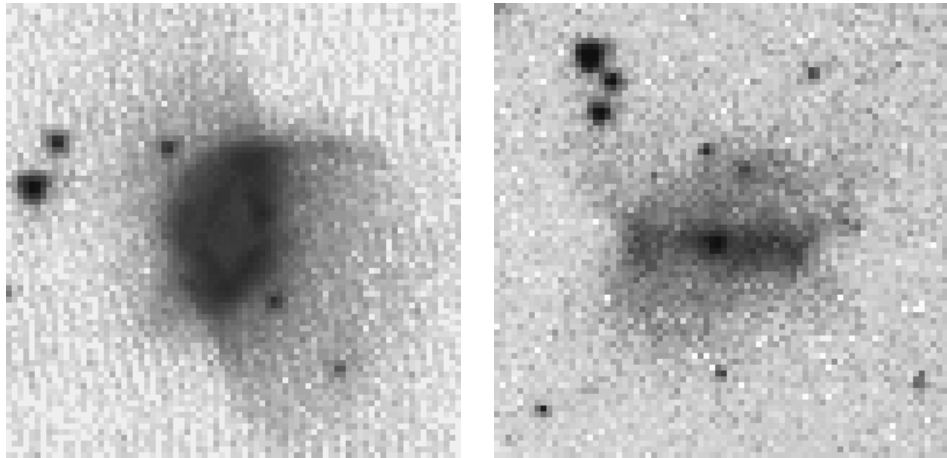


Figure 3. Bipolar PNs: LMC SMP 91 and SMC MA 1682.

from lower mass progenitors (Stanghellini, Corradi, & Schwarz 1993, Stanghellini et al. 2002b).

2.3. The $[\text{O III}]/\text{H}\beta$ distribution

In Figure 4 (left panel) we plot a histogram of the ratio of (reddening-corrected) fluxes of the $[\text{O III}] \lambda 5007$ and $\text{H}\beta$ lines for the PNs of the SMC and the LMC. The median of the SMC distribution is a factor of two lower than for the corresponding LMC distribution ($\langle [\text{O III}]/\text{H}\beta \rangle_{\text{SMC}} = 5.7 \pm 2.5$ and $\langle [\text{O III}]/\text{H}\beta \rangle_{\text{LMC}} = 9.4 \pm 3.1$). This result is free of object selection biases since both sets of targets were chosen in much the same way.

The $[\text{O III}]/\text{H}\beta$ emissivity ratio is physically scaled linearly with the O/H abundance and the fractional ionization of O^{++} . Also it depends exponentially on the local electron excitation temperature, $T_e(\text{O}^{++})$ since electron collisions on the high-energy tail of the free energy distribution excite the transition. Of course, $T_e(\text{O}^{++})$ depends on O/H and O^{++}/O as well. So interpreting the differences between the $[\text{O III}]/\text{H}\beta$ ratios of the SMC and the LMC is best done using ionization models.

Our Cloudy (Ferland 1996) models explore the major line emission in a set of Galactic, LMC, and SMC models with same gas density (1000 cm^{-3}) and different metallicities, adequately chosen to represent the *average* nebula in each studied galaxy, as explained in Stanghellini et al. (2003a). The stellar ionizing spectrum is assumed to be a blackbody with temperatures and luminosities from the H-burning evolutionary tracks for the appropriate galaxian population by Vassiliadis and Wood (1994).

In Figure 4 (right panel) we show the line intensity relative to $\text{H}\beta$ for the major coolants in the SMC, LMC, and Galactic PNs, versus the oxygen abundance, as derived from our simplified Cloudy models. While we have calculated the evolution of these intensity ratios following the evolution of the CS from the early post-AGB phase to the white dwarf stage, we only plot here the flux ratios corresponding to the models with the highest temperature, for each PN composition. In general, our target selection tends to favor targets with hottest

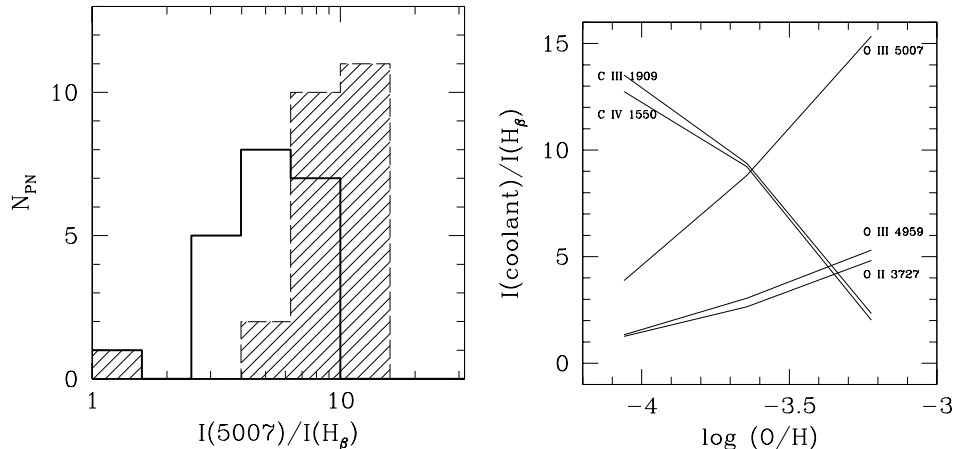


Figure 4. Left: distribution of the [O III] $\lambda 5007$ over $H\beta$ intensity ratios in the SMC (thick histogram) and LMC (shaded histogram) PNs; right: intensity ratios of the major PN coolants over $H\beta$, versus oxygen abundances (from Stanghellini et al. 2003a).

CSs: $T_{eff} \geq 50,000$ K both in the SMC and in the LMC, thus the set of high-temperature models is the most adequate to reproduce the observations for LMC and SMC PNs.

The cooling processes that determine $T_e(O^{++})$ in the SMC, LMC and Galactic PNs are noteworthy. In the Galaxy the primary coolants of PNs with hot CSs are the optical forbidden lines of [O III] $\lambda 5007$ and other lines of O^+ and O^{++} . However, in environments in which O/H is as low as in the SMC, the primary coolants may become ultraviolet intercombination lines of C^+ and C^{++} . The simple models described here seem to reproduce very well the optical flux ratios of PNs in the Magellanic Clouds. It will be interesting to confirm these predictions with future UV observations.

3. Summary

Magellanic PNs are ideal probes to study stellar evolution and populations of low- and intermediate-mass stars. The use of the *HST* is fundamental for determining the PN shapes, the radii, and also to detect the CSs. Furthermore, only with the use of spatially resolved images one can identify the LMC and SMC PNs unambiguously, without the accidental inclusion of compact H II regions in the PN samples.

We have presented some of the results derived from our *HST* programs. We found that PNs have the same morphological types in the Galaxy, the LMC, and the SMC. We also found that the distribution of the morphological types is noticeably different in the SMC and the LMC, and that the LMC seems to be populated by PNs whose progenitors are, on average, more massive.

An empirical relation between the nebular radii and the surface brightness is found to hold in both SMC and LMC PNs, independent of morphological

type. The relation, once calibrated, will be used to determine the distance scale for Galactic extended PNs.

The PN cooling is affected by metallicity, and it seems that the [O III] $\lambda 5007$ emission is not always the ideal line to detect bright PNs in all Galaxies, since the strongest cooling lines in very low metallicity PNs seem to be the UV C III] (and C IV]) semiforbidden emission. While the [O III] luminosity functions for the LMC and the SMC PNs are available from the ground, only *HST* can unambiguously determine whether the selected objects are indeed PNs, or are instead H II regions related to young stellar clusters. Since the ambiguity is metallicity-dependent (see Stanghellini et al. 2003b), the result found here is extremely novel.

The observed Magellanic CSs that we did not discuss here in detail constitute the first sizable sample of CS beyond the Milky Way that has been directly observed. While we found only marginal differences between the LMC and the SMC median CSs masses of the CSs, we need to enlarge the sample of CS whose masses can be reliably measured, given the importance of knowing initial-to-final-mass relation in different metallicity environments (Villaver et al. 2003; Villaver et al. in preparation).

Acknowledgments. My *Magellanic Cloud Planetary Nebulae* collaborators, Dick Shaw, Eva Villaver, Chris Blades, and Bruce Balick, are warmly acknowledged for their contributions to the project.

References

- Ferland, G. J. 1996, *Hazy, a Brief Introduction to Cloudy*, University of Kentucky Dept. of Physics and Astronomy Internal Report
- Stanghellini, L., Corradi, R. L. M., & Schwarz, H. E. 1993, *A&A*, 279, 521
- Stanghellini, L., Blades, J. C., Osmer, S. J., Barlow, M. J., & Liu, X.-W. 1999, *ApJ*, 510, 687
- Stanghellini, L., Shaw, R. A., Mutchler, M., Palen, S., Balick, B., & Blades, J. C. 2002a, *ApJ*, 575, 178
- Stanghellini, L., Villaver, E., Manchado, A., & Guerrero, M. A. 2002b, *ApJ*, 576, 285
- Stanghellini, L., Shaw, R. A., Balick, B., Mutchler, M., Blades, J. C., & Villaver, E. 2003a, *ApJ* 596, 997
- Stanghellini, L., Villaver, E., Shaw, R. A., & Mutchler, M. 2003b, *ApJ*, in press (Paper IV)
- Vassiliadis, E. & Wood, P. R. 1994, *ApJS*, 92, 125
- Villaver, E., Stanghellini, L., & Shaw, R. A. 2003, *ApJ*, in press